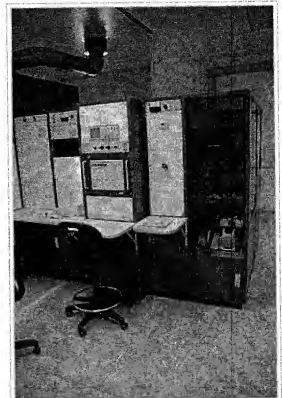


# Ion implantation

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**Ion implantation** is a materials engineering process by which ions of a material can be implanted into another solid, thereby changing the physical properties of the solid. Ion implantation is used in semiconductor device fabrication and in metal finishing, as well as various applications in materials science research. The ions introduce both a chemical change in the target, in that they can be a different element than the target, and a structural change, in that the crystal structure of the target can be damaged or even destroyed by the energetic collision cascades.



An ion implantation system at LAAS technological facility in Toulouse, France.

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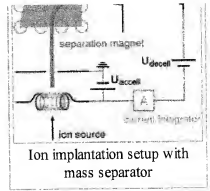
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## General principle

Ion implantation equipment typically consists of an ion source, where ions of the desired element are produced, an accelerator, where the ions are electrostatically accelerated to a high energy, and a target chamber, where the



ions impinge on a target, which is the material to be implanted. Thus ion implantation is a special case of particle radiation. Each ion is typically a single atom or molecule, and thus the actual amount of material implanted in the target is the integral over time of the ion current. This amount is called the dose. The currents supplied by implanters are typically small (microamperes), and thus the dose which can be implanted in a reasonable amount of time is small. Thus, ion implantation finds application in cases where the amount of chemical change required is small.



Typical ion energies are in the range of 10 to 500 keV (1,600 to 80,000 aJ). Energies in the range 1 to 10 keV (160 to 1,600 aJ) can be used, but result in a penetration of only a few nanometers or less. Energies lower than this result in very little damage to the target, and fall under the designation ion beam deposition. Higher energies can also be used: accelerators capable of 5 MeV (800,000 aJ) are common. However, there is often great structural damage to the target, and because the depth distribution is broad, the net composition change at any point in the target will be small.

The energy of the ions, as well as the ion species and the composition of the target determine the depth of penetration of the ions in the solid: A monoenergetic ion beam will generally have a broad depth distribution. The average penetration depth is called the range of the ions. Under typical circumstances ion ranges will be between 10 nanometers and 1 micrometer. Thus, ion implantation is especially useful in cases where the chemical or structural change is desired to be near the surface of the target. Ions gradually lose their energy as they travel through the solid, both from occasional collisions with target atoms (which cause abrupt energy transfers) and from a mild drag from overlap of electron orbitals, which is a continuous process. The loss of ion energy in the target is called stopping.

## Application in semiconductor device fabrication

### Doping

The introduction of dopants in a semiconductor is the most common application of ion implantation. Dopant ions such as boron, phosphorus or arsenic are generally created from a gas source, so that the purity of the source can be very high. These gases tend to be very hazardous. When implanted in a semiconductor, each dopant atom creates a charge carrier in the semiconductor (hole or electron, depending on if it is a p-type or n-type dopant), thus modifying the conductivity of the semiconductor in its vicinity.

### Silicon on insulator

One prominent method for preparing silicon on insulator (SOI) substrates from conventional silicon substrates is the *SIMOX* (Separation by IMplantation of OXygen) process, wherein a buried high dose oxygen implant is converted to silicon oxide by a high temperature annealing process.

### Mesotaxy

Mesotaxy is the term for the growth of a crystallographically matching phase underneath the surface of the host crystal (compare to epitaxy, which is the growth of the matching phase on the surface of a substrate). In this process, ions are implanted at a high enough energy and dose into a material to create a layer of a second phase, and the temperature is controlled so that the crystal structure of the target is not destroyed. The crystal orientation

of the layer can be engineered to match that of the target, even though the exact crystal structure and lattice constant may be very different. For example, after the implantation of nickel ions into a silicon wafer, a layer of nickel silicide can be grown in which the crystal orientation of the silicide matches that of the silicon.

## **Application in metal finishing**

### **Tool steel toughening**

Nitrogen or other ions can be implanted into a tool steel target (drill bits, for example). The structural change caused by the implantation produces a surface compression in the steel, which prevents crack propagation and thus makes the material more resistant to fracture. The chemical change can also make the tool more resistant to corrosion.

### **Surface finishing**

In some applications, for example prosthetic devices such as artificial joints, it is desired to have surfaces very resistant to both chemical corrosion and wear due to friction. Ion implantation is used in such cases to engineer the surfaces of such devices for more reliable performance. As in the case of tool steels, the surface modification caused by ion implantation includes both a surface compression which prevents crack propagation and an alloying of the surface to make it more chemically resistant to corrosion.

## **Problems with ion implantation**

### **Crystallographic damage**

Each individual ion produces many point defects in the target crystal on impact such as vacancies and interstitials. Vacancies are crystal lattice points unoccupied by an atom: in this case the ion collides with a target atom, resulting in transfer of a significant amount of energy to the target atom such that it leaves its crystal site. This target atom then itself becomes a projectile in the solid, and can cause successive collision events. Interstitials result when such atoms (or the original ion itself) come to rest in the solid, but find no vacant space in the lattice to reside. These point defects can migrate and cluster with each other, resulting in dislocation loops and other defects.

### **Damage recovery**

Because ion implantation causes damage to the crystal structure of the target which is often unwanted, ion implantation processing is often followed by a thermal annealing. This can be referred to as damage recovery.

### **Amorphization**

The amount of crystallographic damage can be enough to completely amorphize the surface of the target: i.e. it can become an amorphous solid (such a solid produced from a melt is called a glass). In some cases, complete amorphization of a target is preferable to a highly defective crystal: An amorphized film can be regrown at a lower temperature than required to anneal a highly damaged crystal.

### **Sputtering**

Some of the collision events result in atoms being ejected (sputtered) from the surface, and thus ion implantation will

slowly etch away a surface. The effect is only appreciable for very large doses.

## Ion channelling

If there is a crystallographic structure to the target, and especially in semiconductor substrates where the crystal structure is more open, particular crystallographic directions offer much lower stopping than other directions. The result is that the range of an ion can be much longer if the ion travels exactly along a particular direction, for example the  $\langle 110 \rangle$  direction in silicon and other diamond cubic materials. This effect is called *ion channelling*, and, like all the channelling effects, is highly nonlinear, with small variations from perfect orientation resulting in extreme differences in implantation depth. For this reason, most implantation is carried out a few degrees off-axis, where tiny alignment errors will have more predictable effects. There is no relation between this effect and ion channel of a cell membrane.

Ion channelling can be used directly in Rutherford backscattering and related techniques as an analytical method to determine the amount and depth profile of damage in crystalline thin film materials.



A diamond cubic crystal viewed from the  $\langle 110 \rangle$  direction, showing hexagonal ion channels.

## Hazardous Materials Note

In the ion implantation semiconductor fabrication process of wafers, it is important for the workers to minimize their exposure to the toxic materials used in the ion implanter process. Such hazardous elements, solid source and gasses are used, such as Arsine and Phosphine. For this reason, the semiconductor fabrication facilities are highly automated, and may feature negative pressure gas bottles safe delivery system (SDS). Other elements may include Antimony, Arsenic, Phosphorus, and Boron. Residue of these elements show up when the machine is opened to atmosphere, and can also be accumulated and found concentrated in the vacuum pumps hardware. It is important not to expose yourself to these carcinogenic, corrosive, flammable, and toxic elements. Many overlapping safety protocols must be used when handling these deadly compounds. Use safety, and read MSDS's.

## High Voltage Safety

High voltage power supplies in ion implantation equipment can pose a risk of electrocution. In addition, high-energy atomic collisions can, in some cases, generate radionuclides. Operators and Maintenance personnel should learn and follow the safety advice of the manufacturer and/or the institution responsible for the equipment. Prior to entry to high voltage area, terminal components must be grounded using a grounding stick. Next, power supplies should be locked in the off state and tagged to prevent unauthorized energizing.

## Manufacturers of Ion Implantation Equipment

- Advanced Ion Beam Technology (<http://www.aibt-inc.com>)
- Axcelis Technologies (<http://www.axcelis.com>)
- Complete Ions (<http://www.completeions.com>)
- Facilitation Centre for Industrial Plasma Technologies (<http://www.plasmaindia.com>)
- Global Technologies, R&D equipment and Service (<http://www.global-technologies.fr>)
- Ion Beam Services (<http://www.ion-beam-services.com>)
- Nissin Ion Equipment (<http://www.nissin-ion.co.jp>)
- SemEquip (<http://www.semequip.com>)

- SEN Corporation (a SHI and Axcelis company) (<http://www.senova.co.jp/english/index.html>)
- Tokyo Electron Limited (<http://www.tel.com/eng/about/index.htm>)
- Ulvac Technologies (<http://www.ulvac.com>)
- Varian Semiconductor Equipment (<http://www.vsea.com>)

## External links

- SEMI (<http://www.semi.org>) -- a semiconductor standards clearinghouse and trade organization
- Ion Implantation (<http://www.casetechnology.com/implant.html>)
- James Ziegler's code for simulating ion implantation. (<http://www.srim.org>)
- [1] (<http://www.centrotherm.de>)

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Categories: Materials science | Semiconductor device fabrication | Semiconductor technology | Glass coating and surface modification

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